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The Art and Craft of Coil Construction

Dr Graham Butler M0BDS looks at the practical aspects of coil construction, with specific reference to air cored solenoids and iron-dust cored toroids.

In my opinion, coils form the backbone of any traditional radio frequency (RF) construction project. Yet for many, their design, winding and adjustment is seen as a mysterious art that is beyond the capabilities of all but the most experienced builder. In this article I hope to demystify the humble RF coil. In doing so, my aim is that more constructors, novice and experienced alike, will be encouraged to 'wind their own'.

Why Wind

So why would I want to wind my own coils in preference to buying ready-made devices? There are four main reasons. Firstly, home made coils can be tailored to my exact requirements. Commercially available devices, on the other hand, have a limited range and scope and will always involve a certain amount of compromise. Secondly, homebrewing opens up the opportunity for experimenting. I can easily remove turns from my coil and re-position its coupling windings for best effect. Thirdly, with materials readily available in my house and shack, I can fabricate a new device within half an hour or so. In contrast to this, placing an internet or postal order and waiting for the package to arrive through the letterbox can take several days. Lastly, but by no means least, is the huge satisfaction of making my own fully working coil.

Coils come in all shapes, sizes and core materials. Historically, permeability tuned systems (with ferrite cores that could be slid in and out of a solenoid-style coil) were common in broadcast receivers. So were threaded formers that allowed iron-dust 'slugs' to be screwed in and out of their windings. Indeed, this was a common adjustment method used for intermediate frequency transformers (IFTs). Early radios sometimes used multiple air cored coils that could be moved closer together or further apart by mechanical means. All of these arrangements are interesting from a historical point of view but are rarely used nowadays. For this reason, I shall concentrate on just two styles of coil, namely the air cored solenoid and the iron-dust cored toroid. These are by far the most popular and most convenient forms of the RF coil.

Air Cored Solenoids

Air cored solenoids are the traditional coils that have been used since the very early days of radio. Over the years I have used them for many different applications including tuned circuits, VFO coils, filters and balun transformers. They are easy to wind and can be fabricated on all kinds of former, such as home made cardboard tubes, ballpoint pen cases and plastic drainpipes. My only requirement for choosing a former is that it should be mechanically rigid and a good electrical insulator. Conveniently sized coils can easily be attached to a suitable connector. I have often used this principle to make plug-in coils, one for each amateur band. Nine-pin D-type connectors, as used on computer serial ports, are particularly useful for this purpose.

The approximate inductance of an air cored solenoid can easily be calculated from the formula:

$L = n^2d^2/(l + 0.45d)$

where L is the inductance in nanohenries, n is the number of turns and l and d are the coil length and diameter in millimetres. This is based on a formula published by **Harold Aldon Wheeler** in 1928.

For a resonant air cored coil (tuned circuit), the quality factor (Q) can be obtained from the formula:

$Q = 2\pi fL/r$

where f is the resonant frequency in megahertz, L is the inductance in microhenries and r is the AC resistance in ohms. Note that I have used the used term 'AC resistance' here. At high frequencies, current tends to flow close to the surface of a conductor, a phenomena known as the skin effect. This redistribution of current increases the losses in the wire and therefore makes the AC resistance much higher than the DC resistance (as measured on a multimeter).

We use the term 'skin depth' to describe an imaginary cylinder, close to the surface, where all of the current is considered to flow. For copper wire, the skin depth at 100kHz is about 0.2mm, decreasing to 0.07mm at 1MHz and 0.02mm at 10MHz. I can illustrate this by pointing out that the AC resistance of a 1mm diameter wire operating at 1MHz is roughly four times its DC resistance. At 10MHz, the factor has increased to 12 times! You should, of course, still use the thickest wire possible to obtain the highest Q.

In my opinion, there are four main advantages to using air-cored solenoids. Firstly, they are very easy to construct. Secondly, I have found that they are capable of achieving very high Q values, providing that the wire size and coil dimensions are appropriate for the operating frequency. Thirdly, they are capable of very good temperature stability, provided that the former has good thermal and mechanical properties. Finally, they are ideal for high-power operation because their core (air) cannot magnetically saturate.

I have discovered, however, that, they have one significant disadvantage. Since the solenoid's magnetic field extends well beyond the bounds of coil itself, they are always prone to proximity effects. In other words, nearby objects such as components, circuit boards or even the operator's fingers, can affect the inductance and Q of the device. Coils in close proximity to each other can also interact, causing unwanted feedback or

frequency 'pulling'. I, therefore, recommend that any such coils that are used in frequency-critical applications should be adequately screened.

The photograph, **Fig. 1**, shows a current balun (common-mode choke) that I wound on a length of 30mm diameter cardboard tube. I used plastic-coated wire for its turns and anchored them by passing the wire though holes drilled in the tube. It is suitable for indoor low power (QRP) operation. For outdoors, use a plastic tube instead. Use thicker wire for higher power levels.

The second photograph, **Fig. 2**, shows a tuned circuit that I wound on a 15mm diameter plastic tube. Here I used 0.315mm diameter enamelled copper wire for its turns. A coupling winding is located over the 'earthy' end of the main coil, providing 'tight' coupling. A second coupling winding is spaced clear of the main coil, providing 'loose' coupling. I held all windings in place by electricians tape and used coloured sleeving to identify the six terminations.

Iron-Dust Cored Toroids

Iron-dust cored toroids have become extremely popular in recent times, for both commercial and homebrew use. A wide range of cores are now readily available and, in my opinion, are an absolute must for any well-stocked spares box.

They have three major advantages over their air-cored counterparts. Firstly, they are physically small, making them ideal for mounting on PCB-based and stripboard-based projects. Secondly, their magnetic field remains almost entirely within their core, making them almost completely immune to proximity effects. Thirdly, they require a lot less wire due to the core's higher permeability. This, in turn, significantly reduces losses due to the wire's AC resistance (DC resistance plus skin effect).

On the negative side, I do find that these iron-dust cored toroids are slightly more tedious to construct. I have also found that the core material must be chosen carefully to match the frequency of operation, otherwise the coil's *Q* can suffer. Finally, the core material can saturate if the windings pass high DC or AC currents. My experience is that they are generally fine for QRP operation but require careful consideration and calculation if used for higher power levels.

Table 1 details some of the more popular and readily available Micrometals iron-dust cored toroids. A_l is the inductance factor in nanohenries per turn. The frequency column indicates the frequency range, in megahertz, for which the performance as a resonant circuit is optimal. Operation outside this range is quite acceptable for broadband operation. Dimensions quoted refer to the internal diameter, external diameter and height, expressed in millimetres. I have taken this data from the Micrometals website (below). Most of my toroids are purchased from JAB Electronics (URL also below). I have found that the T50-7 device is particularly suitable for VFO applications due to the material's low temperature coefficient.

www.micrometals.com
www.jabdog.com

Table 1: Some of the more popular and readily available Micrometals iron-dust cored toroids

Part Code	A_l Factor	Frequency (MHz)	Colour	Dimensions (mm)
T50-2	4.9	0.25 - 10	Red	7.7, 12.7, 4.8
T50-6	4.0	3 - 40	Yellow	7.7, 12.7, 4.8
T50-7	4.3	1 - 25	White	7.7, 12.7, 4.8
T68-2	5.7	0.25 - 10	Red	9.4, 17.5, 4.8
T68-6	4.7	3 - 40	Yellow	9.4, 17.5, 4.8
T80-2	5.5	0.25 - 10	Red	12.6, 20.2, 6.4
T80-6	4.5	3 - 40	Yellow	12.6, 20.2, 6.4

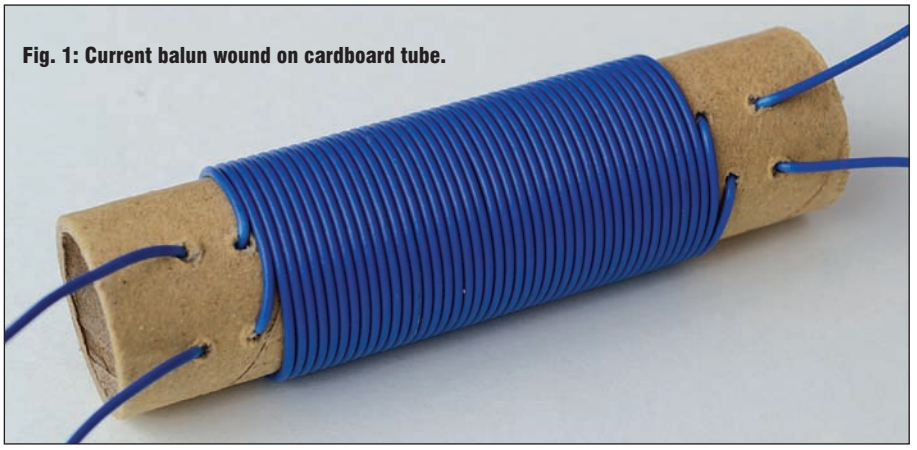
Fig. 1: Current balun wound on cardboard tube.

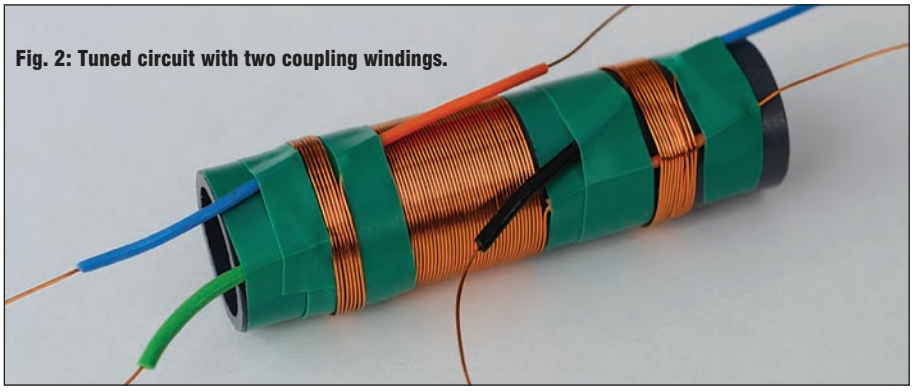
Fig. 2: Tuned circuit with two coupling windings.

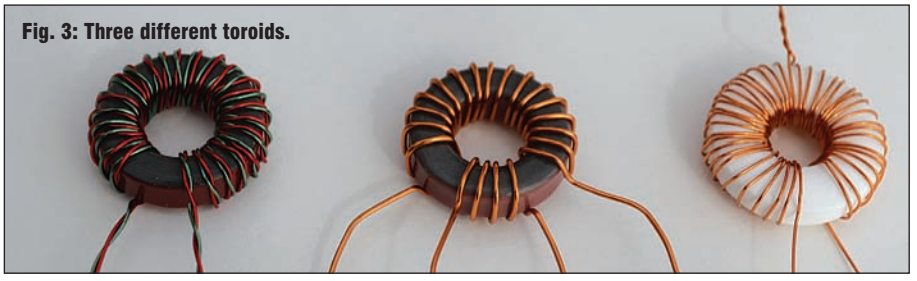
Fig. 3: Three different toroids.

If n is the number of turns then the winding inductance is given by the formula:

$L = n^2A_l$

where A_l is the inductance factor and L is the inductance in nanohenries.

The photograph, **Fig. 3**, shows three different configurations of toroids. The one on the left has a single bifilar winding. I used two different colours of enamelled wire to make the photograph clearer. If you only have one colour, simply identify the ends with coloured sleeving. I twisted the two wires together to give about three twists per centimetre. The toroid in the

centre has one main winding and one coupling winding. I spaced the windings apart to minimise capacitive coupling. Finally, the image on the right shows an air cored (mint cored) toroid using a popular 'mint with a hole' as a former!

The final photograph, **Fig. 4**, shows an interior view of my Elecraft K2 rig. Needless to say, I wound all of the toroids myself.

Practical Hints and Tips

So you have identified an interesting constructional project. You have obtained the necessary coil formers or toroids and have the correct wire to hand. Having calculated the appropriate number of turns for each winding, you are now ready to start. Before winding that first turn, here are some practical hints and tips to make life easier for you.

Start by getting together all the necessary tools and materials that you may require. I always have scissors, wire cutters, electricians tape, coloured sleeving, paper and pencil at the ready. Plan your course of action should the doorbell ring or your dog needs to go out while you are in the middle of a winding. Always have a piece of pre-cut electricians tape handy. Work at an uncluttered worktop in a well-lit location. Daylight is always better than artificial light. Having said that, I find that a craft lamp with built-in magnifier is a great asset. Finally, never do delicate work like coil winding immediately after a physical activity such as DIY or gardening.

Always start with a trial winding of, say, ten turns. This will give a good indication of the total length of wire required and the length of the final winding. After completing the trial winding, you may decide to choose a different wire size. For toroids, the length of wire is particularly important because you will be cutting each piece to length before starting. Don't forget to allow extra length for the terminations.

When winding air cored coils, I always rotate the tube, rather than holding the tube still and winding the wire around it. In the same way, I always rotate the bobbin when paying out more wire from it. Only pay out a little at a time. Never allow a 'wire slinky' to form. Wind slowly and smoothly. I like to keep a constant tension on the wire at all times. If the turns start to open out, gently pack them back together with a fingernail or plastic implement. Never use a screwdriver blade because this could scratch the enamel insulation.

When winding toroids, I always start by cutting the wire to the correct length. Then I pass the length of wire through the hole in the toroid until an equal length protrudes on either side. This counts as one turn. My next step is to hold the wire in place with one hand while passing the free end of the wire through the hole with the other. Keeping the wire taught, continue to wind until half the number of turns have been completed. Then flip everything over and continue winding with the other free end. If you have wound the turns closely and tightly, the winding should stay firmly in place when you let go of the ends.

For windings on toroids, the number of turns is equal to the number of times that the wire passes through the central hole. As a general rule of thumb, try to cover about 80% of the available winding space with wire. Electrically, it makes no difference whether you wind clockwise or anti-clockwise. However, all windings on the same core must be in the same direction. The direction of winding will make a difference to the position of the terminations, important if you are mounting onto an existing PCB.

Sometimes it may desirable to seal the turns of a winding to prevent them from moving. For this I use a mix of two parts PVA glue to one part of water, with just one drop of washing-up liquid added. This same mix can be used to strengthen and seal cardboard tubes. I would advise against using any type of solvent-based glue because this could damage the enamel insulation.

To remove enamel insulation from the terminations, my preferred method is to gently scrape the wire ends with a piece of fine sandpaper. Do this carefully, always drawing the sandpaper away from the coil. Then tin the wire ends immediately, before they have chance to oxidise. I never rely on the heat of a soldering iron to strip so-called 'solder-through' enamel. Sandpaper is much more reliable.

In Conclusion

I do hope that this article has demystified the art and craft of coil construction and encouraged you to have a go yourself. It is really quite easy once you get started. If this has whetted your appetite for more, then do browse the internet for further information and do be prepared to experiment with new ideas and techniques. After all, experimentation is one of the fundamental concepts of amateur radio.

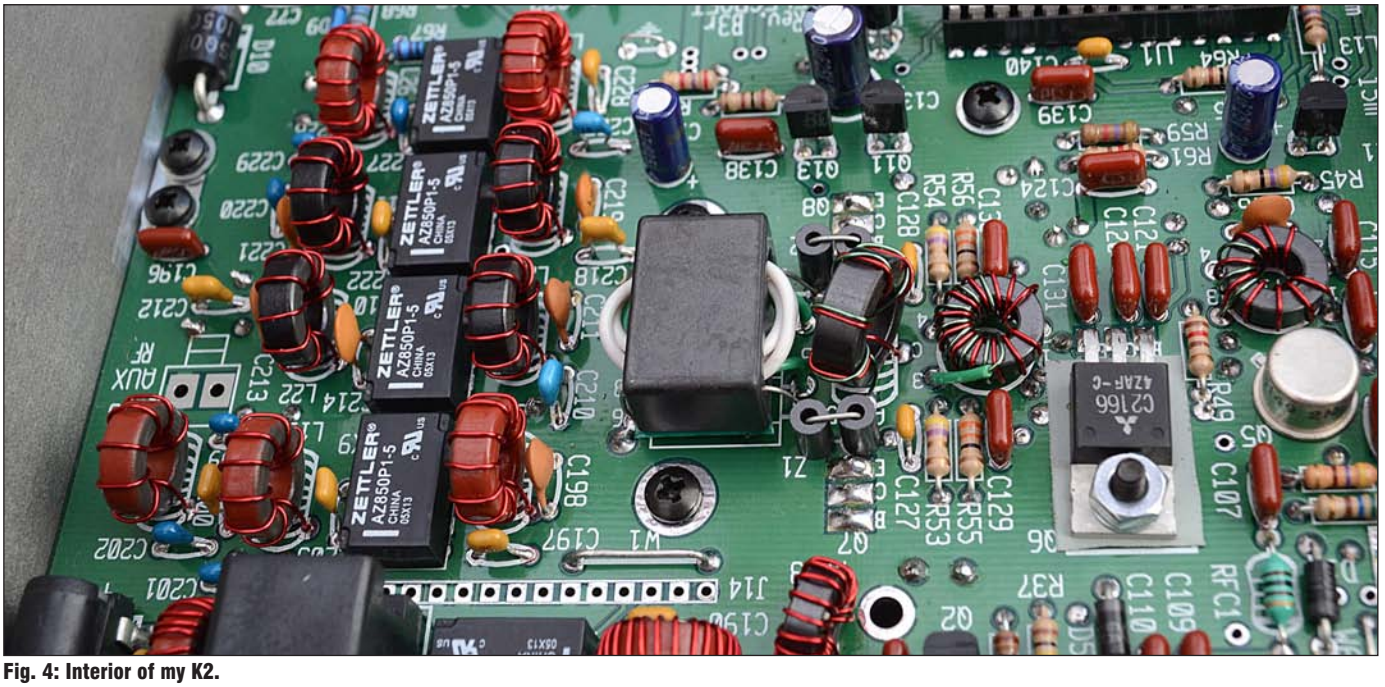

Fig. 4: Interior of my K2.